Temporal changes in precipitation impacting groundwater and stream flow

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Zeitliche Niederschlagsänderungen und deren Einflüsse auf Grundwasser und Abfluss

Introduction

Identification of temporal changes in hydrological variables of the water cycle is an important issue of contemporary hydrology (VAN DAM, 2003). As a result of increases in average surface temperature (IPCC, 2007), whether natural or human-induced, abnormalities in precipitation may have occurred. This in turn could have impacted subsurface water storage, flow regime and in consequence water resources availability for ecosystems. Changes in extreme hydrological events, having recently become more abundant, are attributed to changes in socio-economic systems, changes in terrestrial systems (hydrological systems and ecosystems), and changes in climate (KUNDZEWICZ, 2008). An order of importance of these factors depends on site-specific conditions. In cases of snow-dominated regimes, with maxima in spring and minima in summer or winter, changing patterns of precipitation characterized by intensity, volume, timing and dry spell duration are important factors driving the ongoing intensification of the water cycle.

In this study long–term monthly precipitation records (1956–2008) as well as high resolution radar based precipitation estimates (2004–2008) are analyzed for a small lowland basin in central Poland (Figure 1). The basin is situated within the boundaries of the Kampinos National Park. The main aim of the study is to determine the temporal and spatial patterns of precipitation and to assess its possible impact on shallow groundwater levels and stream flow. The main question addressed is whether meteorological droughts in summer identified at different timescales are becoming more frequent. It is examined if there is an increase in dry summers and – if yes – whether they led to lower groundwater levels and low flows. Although it is difficult to exclude the influence of other specific factors driving the changes over time in terms of river and groundwater behavior, the changes in precipitation as climatic input are considered here as a significant base factor.

Data

A longterm monthly precipitation dataset was used to derive precipitation indexes in order to capture possible changes. The time period that the dataset covers ranges from 1956 to 2008. Areal estimates of precipitation sums were calculated based on Thiessen polygon method. Data

Zusammenfassung

Ziel der vorgestellten Untersuchung ist die Analyse der Niederschlagsverteilung in den Niederungen Zentralpolens und der damit verbundenen Dürrephasen während des Sommers. Dabei wurden Änderungen im Niederschlag mit beobachteten Grundwasserständen und Abflüssen verglichen und es zeigte sich innerhalb der letzten Jahre ein signifikanter Rückgang des Sommer-Niederschlags und eine Zunahme der Dürrehäufigkeit, basierend auf 3-, 6- und 12-monatigen Niederwasseranalysen. Zur Verbesserung der räumlichen Niederschlagsschätzung wurden neben dem regulären Beobachtungsnetz auch Radardaten mit einbezogen. Es zeigten sich anhand der Periode 2004 bis 2008 ungleichförmige Niederschlagsverteilungen im Untersuchungsgebiet mit bis zu 100 mm/a geringeren Niederschlägen im Westen. Die extremsten Ereignisse (maximale und minimale Monatsniederschläge) der Untersuchungsperiode 1956–2008 traten im Jahre 2006 auf.

Schlagwörter: Niederschlagsmuster, Radar, Grundwasser, Niederschlagsänderung.

Summary

In recent years there has been an apparent increase in the occurrence of extreme hydrological events in Poland. The central part of the country has the lowest precipitation with annual totals falling below 600 mm. The objective of this study was to investigate changes in precipitation in a lowland basin located in central Poland where severe frequent meteorological and hydrological droughts appear especially in summer. The focus was on the precipitation evolution that has occurred in the past six decades as well as on the possible shifts in the groundwater levels and stream flow regime induced by changes in precipitation. The Standardized Cumulative Annual Deviation was used to examine the sequences of dry and wet years. Trends detected in the long–term precipitation course were followed by the course of groundwater levels and stream flow. Significantly reduced summer precipitation has occurred during the last decade. Drought frequency evaluated by the Standardized Precipitation Index SPI has changed. As a signature of an intensification of the water cycle the number of 3-, 6- and 12-month droughts has significantly increased. Risk of occurrence of low groundwater levels and reduced stream flow has also increased as a response to tendencies in precipitation. As the raingauge network is too sparse to provide an adequate spatial coverage of precipitation, estimates at higher resolutions (1x1km) were acquired for the period 2004–2008 as a product derived from the weather radar. Monthly precipitation estimates from the rain gauge network correlate well with the radar estimate at a 1 km pixel, however they generally underestimate the areal precipitation in the basin. Spatial precipitation patterns derived from radar data show distinct gradients across the basin. From 2004 to 2008, the western part of the basin has received on average less precipitation than the eastern part. This concerns values for the summer half of the year as well as for the whole year. Differences reach over 100 mm/year. Extremely low precipitation has appeared in July 2006, however it was followed by extremely high precipitation in August 2006. Both are absolute values of monthly precipitation in the period 1956–2008.

Key words: Rain gauge rainfall, weather radar rainfall, spatial patterns, temporal changes.

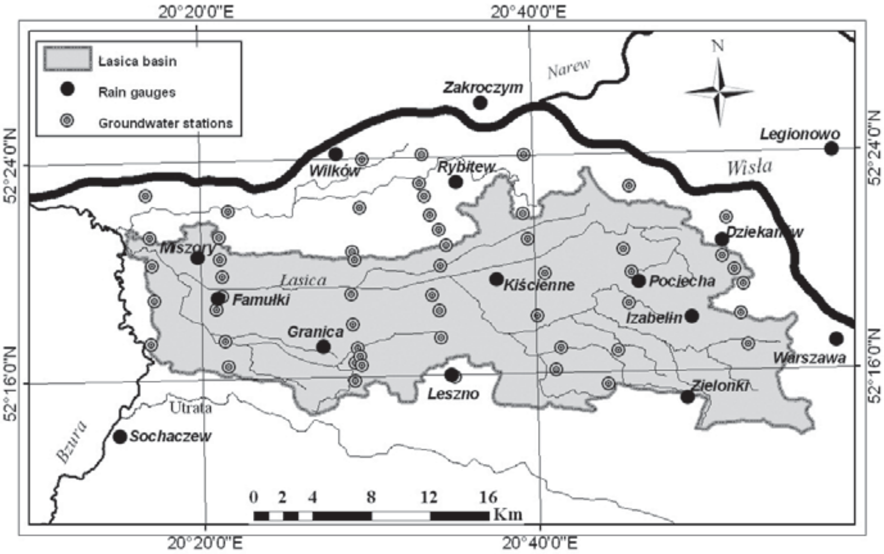

Figure 1: Location of raingauge and groundwater monitoring network in the Lasica basin, central Poland

Abbildung 1: Lage der Niederschlags- und Grundwassermessungen im Lascia Gebiet in Zentralpolen

were available from six rain gauge stations belonging to the network of the Institute of Meteorology and Water Management in Warsaw and from nine stations belonging to the network of the Kampinos National Park (Figure 1). Owing to aerodynamic errors, correction of precipitation measurements was carried out. As the rain gauge measurements are representative only at the measurement site and are biased estimates of the precipitation, radar precipitation data at high spatial resolution were acquired as a product derived from the weather radar situated in Legionowo (latitude: 52°24'01", longitude: 20°55'53"), north to the analyzed basin. This weather radar (model Meteor 1500C) belongs to the Polish radar network POLRAD covering the whole Poland territory and is operated by the Institute of Meteorology and Water Management (Szturc, Dziewit, 2005). The temporal resolution of the data is 10 min, the spatial resolution is 1 km and they are quality controlled (Szturc et al., 2010). Based on that, 3h-interval data were aquired for this study. Then monthly radar estimates in 2004–2008 integrated from 3h-interval data were applied to analyze spatial patterns of precipitation.

In addition to the precipitation data, groundwater and discharge data were used in this study. Groundwater records represent depth to the groundwater measured every two weeks since 1998 in the network of 56 piezometers belonging to the Kampinos National Park. Besides, long-term observations of groundwater were conducted by the Institute of Meteorology and Water Management in six piezometers. One of them (Korfowe piezometer) was continuously observed from 1956 to 2000 and its groundwater levels correlate well with piezometer No.P22 of the KNP network (Figure 2a). Both of them reflect well groundwater stages in lowland areas of the basin (Figure 2b). Thus the average shallow groundwater levels in the period 1956–1998 were reconstructed using relationships approximated by simple regression models. First, groundwater levels in the piezometer P22 were reconstructed, and then the average shallow groundwater levels in lowland areas were inferred for the period 1956–1998. Average shallow groundwater levels in the lowland areas of the basin were used to construct flow duration curves for the period 1956–2008.

Daily discharge data of the Lasica at the cross-section Wladyslawow, covering a basin area of about 363 km^2 were used in the analysis of flow duration curves for the period 1956–2008.

Methodology

In order to track long–term fluctuations in precipitation, two indicies were applied: the Standardized Cumulative Annual Deviation (SCAD) and Standard Precipitation Index (SPI). The SCAD function was applied for annual values, whereas the SPI analysis was performed using the monthly sums of precipitation for the long-term period of 1956–2008. The SPI was calculated for each month at 3-, 6-, 12-, 24- and 48-month timescales. According to classification of the SPI values for the conditions of central Poland, drought starts if the value of the SPI is equal or less then –0.5 (Labedzki, 2007). Thus the number of months with droughts for each timescale was identified for the summer half of the year (May–October) and then the number of droughts per 100 years was calculated according to Labedzki (2007) as: $N_{i,100} = (N_i / i\ n)\ 100$, where: $N_{i,100}$ – the number of droughts for a time scale i in 100 years, N_i – the number of months with droughts for a timescale i in the n–year set, i – timescale (3, 6, 12, 24, 48 months), n – the number of years in the data set. The frequency of droughts was evaluated for summer months (May–October) in three sub-periods of 1956–2008, namely in 1956–1980, 1981–2000, and 2001–2008.

For the assessment of the impact of changes in precipitation on groundwater and stream flow, the SCAD function was applied to annual series of groundwater levels and stream flow. Besides, the depth-duration curves and flow duration curves were constructed to evaluate the percentage of time groundwater or stream flow was equal or less.

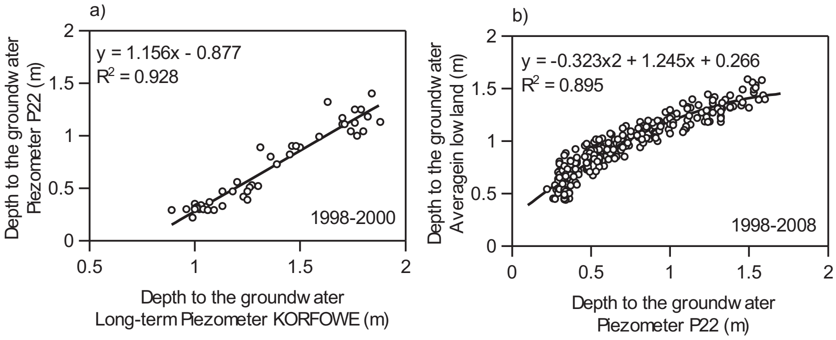

Figure 2: Regression used to reconstruct average shallow groundwater levels in the period 1956–1998: relationship between groundwater levels in piezometer Korfowe in the old network and piezometer P22 in the current network (a), relationship between groundwater levels in piezometer P22 and average shallow groundwater levels

Abbildung 2: (a) Regressionsbeziehung zwischen den Grundwassermessstellen Korfowe und P22 für den Zeitraum 1956–1998. (b) Regressionsbeziehung zwischen der Grundwassermessstelle P22 und mittleren Grundwasserständen des Tieflands

Results and discussion

Temporal changes in precipitation and drought frequency

A positive slope of the SCAD was detected in the period 1956–1980, whereas from 1981 to 2000 and from 2001 to 2008 a dominating negative slope was a signal of periods with values lower than the long-term mean (Figure 3a). Such tendencies were found for all three variables namely precipitation, groundwater levels and stream flow. In the period 2001–2008 monthly precipitation sums in June and July were much lower than in the period 1956–1980 and 1981– 2000 (Figure 3b). In the summer half of the year (May–October) precipitation was on average approximately 60 mm lower in the period 2001–2008 than in the period 1956– 1980 and 30 mm lower than in the period 1980–2000 (Figure 3c). The time series of the monthly values of SPI for selected time scales are presented in Figure 5. For shorter timescales there are more frequent seasonal and inter-annual precipitation variations, giving a high number of drought events. Short-term extreme summer droughts have appeared in 1959, 1969, 1992, 2000, 2005 and 2006. Transforming the number of events N_i into the number of droughts in 100 years one could expect about 52, 58 and 75 droughts of 3-month duration respectively in the periods 1956–1980, 1981–2000 and 2001–2008 (Table 1). Thus the frequency of events of short duration (3- and 6-month) has increased in recent years. However, the recent 2001– 2008 droughts are not the worst droughts that have occurred in the recorded history.

Spatial patterns of precipitation inferred from radar estimates

Compared to conventional rain gauge networks, the weather radar provides precipitation estimates at enhanced spatial and temporal resolution. High resolution and continuity of the measurements make available detailed information about spatial pattern of precipitation field however not free from errors (EINFALT et al., 2010). Sources of errors in radar data are known but it is very difficult to quantitatively assess uncertainty of the data (SZTURC et al.,

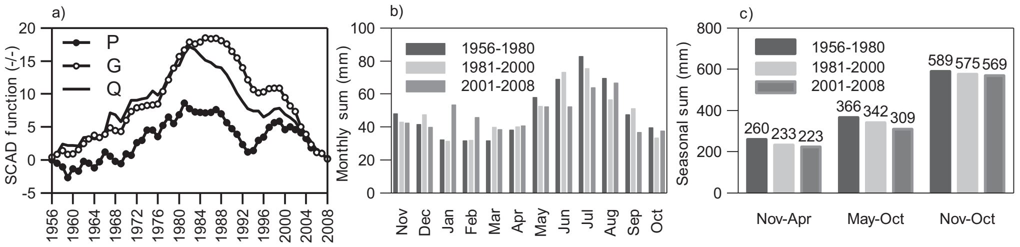

Figure 3: Standardized Cumulative Annual Deviation of precipitation (P), groundwater levels (G) and stream flow (Q) (a), monthly precipitation sums in the sub-periods 1956–2008 (b), seasonal and annual precipitation sums in the sub-periods of 1956–2008 (c)
Abbildung 3: (a) Prozentuelle jährliche Änderung von Niederschlag (P), Grundwasserstand (G) und Abfluss (Q). (b) Monatlicher Niederschlag innerhalb der Vergleichsperioden 1956–2008. (c) Saisonaler Niederschlag innerhalb der Vergleichsperioden 1956–2008

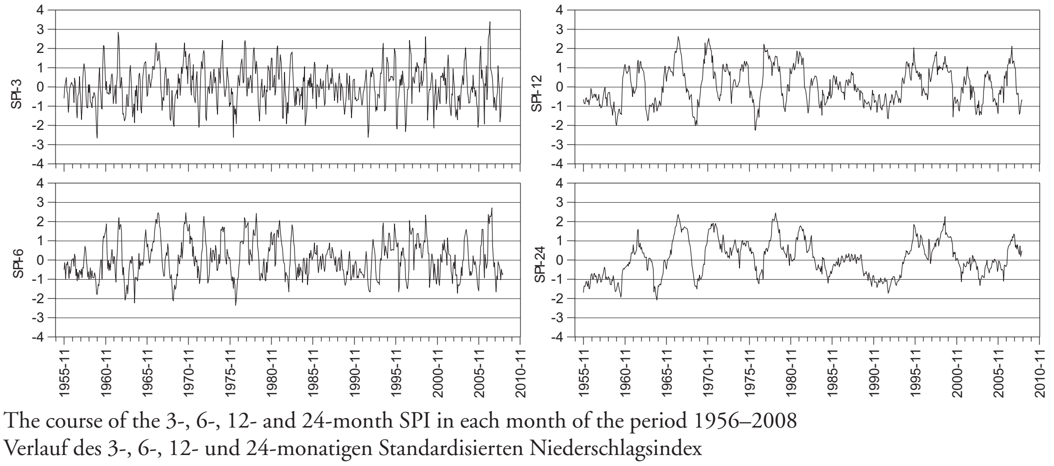

Figure 4: The course of the 3-, 6-, 12- and 24-month SPI in each month of the period 1956–2008
Abbildung 4: Verlauf des 3-, 6-, 12- und 24-monatigen Standardisierten Niederschlagsindex

Table 1: Number of months (N_i) with summer drought (SPI < –0.5) computed with the SPI for 3, 6, 12, 24 and 48 month timescale and number of summer droughts ($N_{i,100}$) per 100 years for the considered timescales
Tabelle 1: Anzahl der Monate (N_i) mit Sommerdürre (SPI < –0.5) und Anzahl der Monate (N_i) mit Sommerdürre anhand ($N_{i,100}$)/100 Jahre

Timescale (months)	1956–2008		1956–1980		1981–2000		2001–2008	
	N_i	$N_{i,100}$	N_i	$N_{i,100}$	N_i	$N_{i,100}$	N_i	$N_{i,100}$
3	92	58	39	52	35	58	18	75
6	109	34	51	34	41	34	17	35
12	105	17	48	16	35	15	22	23
24	95	7	47	8	35	7	13	7
48	97	4	44	4	36	4	17	4

2010). These errors can be reduced by applying adjustments and corrections to the radar-derived precipitation estimates. In this case data were filtered to remove anomalous radar echo (speckle noise and permanent echo) and then adjusted using gauge-to-radar technique. The added value expected from using gauge adjusted radar product is to measure the precipitation over the entire area observed by the radar which intuitively is better than a single gauge. Finally, radar rainfall was checked versus gauged rainfall using monthly sums in years for the period 2004–2008. At pixel scale a relatively good correlation was obtained. However, gauged rainfall underestimates the areal estimates derived from radar data (Figure 5). Examples of spatial patterns of precipitation inferred from radar estimates are presented in Figure 6. In the years 2004–2008 the western part of the basin has received on average less precipitation than the eastern part. This concerns values for the summer half of the year, as well as for the whole year. Differences reach over 100 mm/year. This causes unfavorable conditions for valuable, protected wetlands located in thewestern part of the basin, recognized as key ecosystems. Extremely low precipitation was recorded in July 2006. However, this was followed by extremely abundant precipitation in August 2006. The average areal monthly sum was 10 mm in July 2006 and 160 mm in August 2006. Both values are absolute values of monthly precipitation in the period 1956–2008.

Impact of precipitation changes on streamflow and groundwater levels

Flow Duration Curves derived from daily stream flow data show a gradual change; in the period 2001–2008 low flows lasted much longer than in the period 1981–2000 and 1951–1980 (Figure 7a). Risk of occurrence of low flows in summer months has increased from 25% in years 1956–1980 to 53% in recent years of 2001–2008. Corresponding gradual change in groundwater levels with a tendency for long lasting lower levels is observed (Figure 7b). The probability of occurrence of groundwater levels below the target value of –0.8 m below the surface has increased from 26% to 72%.

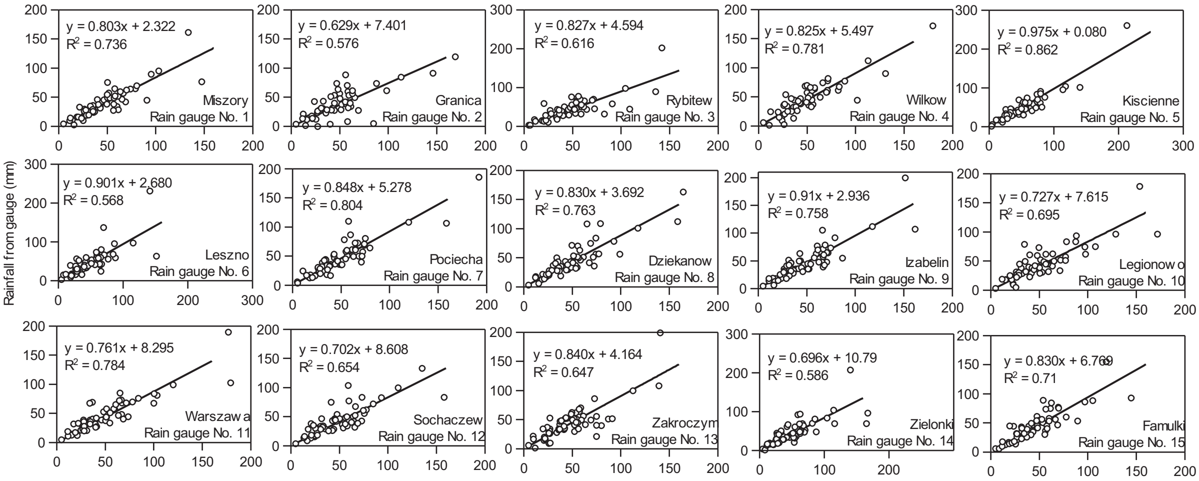

Figure 5: Radar estimated rainfall versus gauge rainfall, monthly sums for the period 2004–2008
Abbildung 5: Gegenüberstellung der Monatssummen des mit Radar geschätzten Niederschlags mit dem Stationsniederschlag (2004–2008)

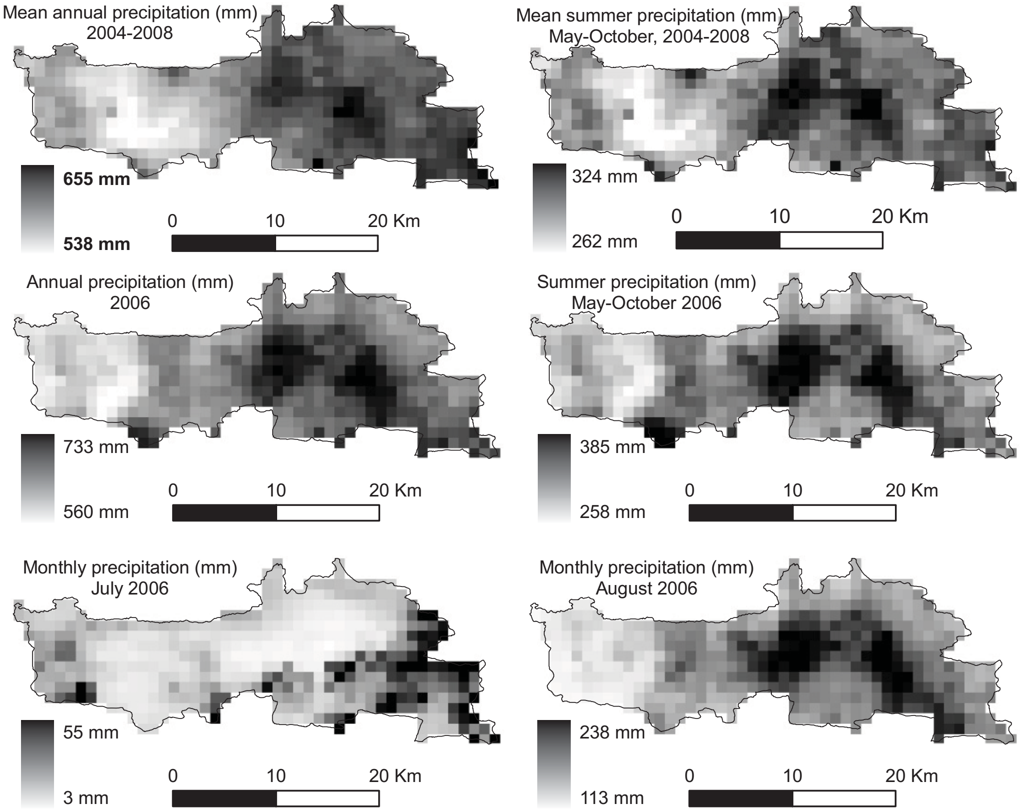

Figure 6: Spatial patterns of precipitation inferred from radar precipitation estimates

Abbildung 6: Räumliche Niederschlagsmuster aus Radarbeobachtungen

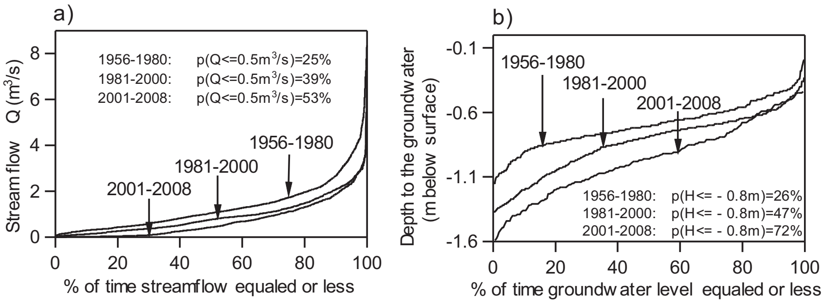

Figure 7: Flow duration curves for stream flow of the Lasica basin at Wladyslawow (a), Depth Duration Curves for groundwater levels in lowland areas in the Lasica basin (b)

Abbildung 7: Dauerlinien des Abfluss am Pegel Wladyslawow (a) und des Grundwasserabstichs im Tiefland des Lasica Gebiets (b)

Conclusions

The presented approach facilitates the identification of changes in precipitation described by shifts in frequency of summer droughts appearance. Signals of an intensification of the water cycle have been detected using precipitation indices over the period 1956–2008. Enhanced understanding of quantitative relationships between increased summer drought frequency and decreased groundwater levels and stream flow is revealed through the consideration of the risk of their appearing. Investigated relationships confirm the substantial drying of the basin caused by an increase of the number of 3-, 6- and 12-month droughts in the last decade whereas the number of long lasting droughts has not been changed.

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References

EINFALT T., SZTURC J., OSRODKA K. (2010): The quality index for radar precipitation data: a Tower of Babel? Atmos. Sci. Let., 11, 139–144.

VAN DAM J.C. (ed.) (2003): Impacts of Climate Change and Climate Variability on Hydrological Regimes. UNESCO International Hydrology Series, Cambridge University Press.

IPCC Climate Change 2007: The Physical Science Basis, 2007. Working Group I Contribution to the Fourth Assessment Report of the IPCC Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK & New York, NY, USA.

KUNDZEWICZ Z.W. (2008): Hydrological extremes in the changing world. Folia Geographica ser. Geographica–Physica, Vol. 39, 37–52.

LABEDZKI L. (2007): Estimation of local drought frequency in central Poland using the standardized precipitation index SPI. Irrigation and Drainage 56(1), 67–77.

SZTURC J., DZIEWIT Z. (2005): Status and perspectives on using radar data: Poland. In: Use of radar observations in hydrological and NWP models. COST Action 717, Final report, Luxembourg 2005, 218–221.

SZTURC J., OSRODKA K., EINFALT T., JURCZYK A. (2010): Rainfall and runoff ensembles based on the quality index of radar precipitation data. In: Proc. 6th European Conf. on Radar in Meteorology and Hydrology: Adv. in Radar Technology, Sibiu, Romania.

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